ARTSN: PROTOTYPE FOR AN AUTOMATED REAL-TIME SPACECRAFT NAVIGATION SYSTEM

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Abstract

The Automated Real-Time Spacecraft Navigation system (ARTSN) is a prototype of a new class of software for automated spacecraft navigation and monitoring. This prototype will lead to improvements in the efficiency of the navigation analysis process, enabling simultaneous support of additional spacecraft by a single analyst. Additionally, faster orbit solution generation, relative to manual systems, reduces the turn-around time between critical events and the required response, allowing new modes of operation with increased reliability and reduced costs. This is especially important during critical events such as the launch phase, aerobraking, maneuver monitoring, and approach.

The current ARTSN prototype has four components: a data pre-processor, a shell interface, an engine, and data displays. To date, there have been end-to-end demonstrations of ARTSN capabilities across several deep space missions. In mid-1997, ARTSN was tested processing raw data from the end of Mars Pathfinder interplanetary cruise, displaying post-fit residuals and updated Mars encounter estimates. ARTSN displays were also used by the Mars Global Surveyor navigation team to observe and make a 'quick-look' assessment of the Mars Orbit Insertion (MOI) maneuver. In early 1998, the Near Earth Asteroid Rendezvous (NEAR) navigation team used the ARTSN pre-processor to assess the execution of several spacecraft maneuvers.

Introduction

ARTSN is a prototype of a data-driven navigation software system which autonomously processes radiometric tracking data for orbit determination. ARTSN validates and corrects observables received via a network connection or file; the receipt of these observables triggers (1) the integration of spacecraft state vectors and dynamic partial derivatives needed to (2) calculate the computed observable and partial derivatives of the observable with respect to relevant parameters. ARTSN then computes (3) estimates of parameters along with their uncertainties and (4) mappings of the spacecraft states and uncertainties to other epochs. In this section overviews are given of the motivation for this system, its development history, and some of its characteristics. The appendix includes a listing of present ARTSN capabilities.

Motivation

Historically, all interplanetary missions have made use of ground-based radio metric data, such as Doppler and range. Additionally, some missions have made use of optical images of target bodies against a known star field, telemetered to the Earth for processing, to provide target relative position information. With all of these data types, the information is electronically transferred to a ground operations facility, where the data is buffered and stored until processed; the latency between observation time and processing time may be from as little as 10 minutes to as long as a few months (depending on the needs of the mission), with 12-24 hours being typical.

Newly received data is merged with already analyzed data and the entire data set is processed via a batch-sequential least squares estimator. In this process, the identification and correction or deletion of invalid data as well as the operation of the software is performed by an analyst operating at a workstation console. The process of fitting the data requires the use of multiple software links and the manual examination of pre-fit residuals to determine which points should be fit and which points should be deleted from the solution. After generating the best estimate of the spacecraft trajectory based on

the input models, the analyst must determine the appropriate set of output coordinate frames and mappings that are desired to view the solution and use the software to generate post-fit residuals. Typically this process requires approximately one hour of additional processing time after the data is received by the operations analyst. When it is necessary to evaluate multiple models, as is the normal procedure, multiple analysts must work in parallel or additional processing time is required.

While recent missions have begun to institute greater automation of portions of the orbit determination process, the nature of the automation focuses on the use of scripts and automated routines which use the legacy software instead of the development of a robust system intended for automated use. Although such automated systems have been developed for Earth orbiting missions, they have not previously existed for interplanetary missions. With such a system, one could automate the generation of predicted spacecraft positions for ground stations, and provide an operational tool for fast turn-around applications. This system is making ground automation of interplanetary navigation tasks more routine, and is serving as a 'stepping stone' to an on-board interplanetary navigation system.

Development

The conceptual design of ARTSN was begun in 1994 by Pollmeier and Masters[1] at the Jet Propulsion Laboratory (JPL). The resulting high-level design, referred to as RTAF (Real-Time Automated Filter), brought out several key lessons:

- Modularize the system architecture whenever possible.

- Separate the data output & control user interfaces from the primary analysis system.

- Use commercial software when possible.

- Streamline the process for addition of new force and observable models.

From RTAF, the next step was to build the ARTSN prototype, with the short-term objective of demonstrating automated radiometric data processing and orbit determination for interplanetary cruise. The authors performed the development and testing of the prototype, investing approximately 2.5 work-years in the effort. Automated orbit determination with ARTSN was first demonstrated in late June 1997; based on the success of these demonstrations, a new effort was initiated in late 1997 to create a 'next generation'

navigation software set, which will be closely allied to the architecture from the ARTSN effort. In addition, the data pre-processor has evolved beyond the prototype state, and is being delivered to flight projects in the summer of 1998.

Characteristics

From the lessons learned in the development effort came the following characteristics of the ARTSN design:

- The (historically) separate modules are integrated into a single package. Merging the links that provide trajectory propagation, station location computation, measurement modeling, filtering, and state and covariance mapping facilitates real-time capability.

- Modern software techniques were used to implement the existing algorithms. The resulting highly modular components can thus be modified easily.

- Interfaces in the packages were arranged to facilitate the system's use in a distributed environment.

Except for some of the graphical user interfaces (GUIs) and some of the low level file readers, all of the code was written in C.* The ARTSN prototype only requires an American National Standards Institute (ANSI) C compiler in order to run on a particular platform. The ARTSN code is not purely object oriented. However, the code is arranged into objects, and these objects in spirit do fit the 'black box' metaphor usually given to object oriented programming; that is, the object contents are encapsulated so that a programmer using the object wouldn't have to know the contents of the object itself.

The design of the ARTSN system allows several new modes of operation to be performed that have previously been unavailable to the interplanetary navigator:

Data Driven Operation

In the current JPL operations navigation software suite, the analyst acts as the 'measurement manager'; that is, no computed measurements, pre-fit residuals, or measurement partials are calculated until the user runs the appropriate software link. The analyst must decide how much data is sent to the link at the time of execution. When the link is executed, the number of points processed is known and fixed; the arrival of new data does not trigger any new activity. In ARTSN, there is a simple measurement manager included in the

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* This was a choice driven by the programming backgrounds of the developers, not by any performance or compatibility criteria.

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engine; with this manager, the system is driven by the arrival of data. No user interaction is needed to process new data; all the relevant calculations are performed upon the arrival of each observable.

Filtering Options

In the current JPL operations navigation software suite, the analyst performs trajectory estimation using a batch sequential filter. Complete data sets are iterated on using a reference trajectory in order to converge to the best solution. Using this system, it is very difficult (if not impossible) to process new data in real time. While the ARTSN system can also operate in this mode, its real strength is the ability to process data using an Extended Kalman Filter (EKF). This approach updates the models and the trajectory as each data point is received. The solution at any given time is the best estimate of the trajectory (and can be viewed in real time).

Information on Demand

The ARTSN "measurement modeling" module, upon receipt of a data point, requests state and partial information about a specific measurement type and time from the "participant" and "propagator" modules (that is, the portions of the system that deals with trajectory and dynamic partial information). Likewise, the "parameter predictor" task requests estimate and covariance information from the same modules at specific mapping times. ARTSN can be configured to any pieces of information after specified amounts of time have elapsed or a certain number of data points have been processed. This allows real time display to be automatically updated, giving an analyst rapid access to a wide variety of information.

Description

Figure 1 shows the ARTSN components, as well as the data flow throughout. The current ARTSN prototype has four types of components: a data pre-processor, a shell interface, an engine, and data displays. The interaction between the components is handled with machine portable data structures of XDR (eXternal Data Representation) encoded binary packets through TCP/IP network connections.

ARTSN receives tracking data (which contains Doppler and range measurements) from the Deep Space Network (DSN) stations in the TRK-2-15A format, a bit-packed format transmitted over a UDP connection. This raw tracking data is unpacked, corrected, and reformatted in real time by the ARTSN pre-processor.

Data Pre-Processor

The data pre-processor, referred to as ARDVARC (Automated Radio metric Data Visualization and Real-time Correction), creates measurement records from the raw DSN date stream. ARDVARC has four major capabilities:

(1) Validation and correction of radio metric tracking data,

(2) Export of validated observables to real-time and off-line orbit determination software,

(3) Real-time monitoring and analysis of radio metric data residuals,

(4) Real-time monitoring of the tracking of a spacecraft across all DSN stations (e.g. a history of what stations have been tracking the spacecraft of interest).

The inputs to the ARDVARC process include station locations and light time information between the spacecraft and ground stations. ARDVARC is a data-driven pre-processor; upon receipt of a series of Doppler phase counts, ARDVARC attempts to build a Doppler observable. Should this candidate observable pass a series of consistency checks, ARDVARC, using self-generated view period information, then creates a list of candidate uplink stations, and creates "hypothetical residuals" and residual rates to determine which station most likely transmitted the signal (no information about the identity of the transmitter is encoded in the signal). Once a transmitter has been selected, the configuration data are examined and corrected, resulting in a logically consistent series of data points.

To illustrate the comparison of hypotheses, Figure 2 shows "hypothetical residuals" built during a tracking handover of Mars Global Surveyor (MGS) coverage from the Deep Space Network station (DSS) 15 (at the Goldstone complex) to DSS 45 (at the Canberra complex). The residuals on the relatively straight portion correspond to the correct hypothesis at any given time (The absolute magnitude of the true MGS pre-fit residuals (~tens of Hz) is due to errors in the predicted trajectory due to aerobraking). Initially, two-way and three-way Doppler is being received at both stations 15 and 45. DSS 15 is the transmitting station. Shortly after 01:35:00 (Earth receive time), DSS 15 stops receiving data. At approximately 01:52:00, (one round-trip light time later) the DSS 45 "hypothesis" becomes correct; DSS 45 is now the transmitting station. By inspection it is relatively easy to identify the "correct" transmitter in this figure; the ARDVARC transmitter selection algorithm uses residuals and

residual rates to perform a similar operation in real-time..

The resulting validated data points can then be output via XDR packets (to the ARTSN engine) or to a file (in this case an Orbit Data File (ODF), for use by the operational DPTRAJ/ODP software suite). The ARDVARC pre-processor is an example of a system compatible with existing operational software and prototypes of future interplanetary navigation software.

ARDVARC can be operated through a graphical user interface (GUI) called XARDVARC; from this interface, analysts can control many inputs in real time, such as

• Doppler observable count time

• Times to create up-to-the-minute ODFs

• Thresholds for accepting/rejecting residual values

XARDVARC has graphical displays for: (1) real-time results of the ongoing validation/correction process, (2) a text summary of the problems corrected, (3) a user-interactive (scaleable, resizeable, with labeling capability) plot of all Doppler and range residuals, (4) an algorithm for making a 'quick-look' assessment of the line-of-sight component of a maneuver (without any *a priori* information about the event), and (5) a station coverage monitor based on the validated data built by ARDVARC.

Shell Interface

The ARTSN shell (ash) is a command-line style interactive user interface that translates namelist inputs into engine commands (for a locally executing engine or one running on a remote machine). The shell serves as the primary means for controlling data sources and the execution of the ARTSN engine. The shell follows a simple command line style parsing algorithm with on-line help for each of the shell commands. Figure 3 depicts a typical ARTSN session (operating in batch sequential mode) on a UNIX workstation, with explanations of the shell commands used.

The ARTSN shell has two primary configurations, both of which can be used in real-time and off-line capacities. One configuration, referred to as the 'network' configuration, is used when the engine is running on one processor, with the input and output activities possibly on other processors. In this case, the ARTSN remote shell is used to communicate with the engine using remote procedure calls over a TCP/IP connection. The second configuration, referred to as the 'stand-alone' configuration, has the system running on a single

processor. In terms of Figure 2, the ARTSN shell and engine boxes are now combined into a single process.

Engine

The ARTSN engine is the primary computation module. Modules in the engine perform trajectory integration, measurement observable computations, filtering, event detection, and parameter mapping. Overall, the major tasks that are performed by the ARTSN objects are depicted in Figure 4. Note that these are major tasks, and not definitions of the objects themselves; that would be beyond the scope intended for this paper.

The ability of the engine to be remotely commanded allows the input and output processes to be modified for specific projects and users without the need to modify (and re-test) the engine. The majority of the algorithms implemented into the ARTSN engine were originally derived for the existing navigation software set. [2,3] The modeling configuration and general data inputs required by the engine are handled through namelist files.

Participants

Interior to the ARTSN software, the primary means of book keeping and storing model data is through the concept of a participant. The term 'participant' encompasses all 'things of interest' in any navigation scenario. Participants include tracking stations, spacecraft (probes), and natural bodies (including satellites, asteroids, and comets). This system is designed to easily allow for the scaling of the number of new bodies, stations, etc. knowing that all existing physical considerations (forces, rotations, etc.) are available to these new participants. One of the primary attributes of a participant is the concept of a dynamic state. Each participant knows it's own state (at any time) with respect to another participant (it's parent). Using this approach a "state tree" can be created in which relative states between any two participants can be easily computed by walking the state tree. The actual state on each leg of the tree is computed by a participant's propagator.

Propagators

To compute the relative states for any two participants, their states must be "propagated" to the correct time and coordinate frame. Each leg of the state tree can be propagated independently by different algorithms. This approach makes it easy to mix different methods of computation from simple conics up to high fidelity numerical integration. ARTSN has three classes of state propagators:

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- *Ephemeris.* The position and velocity of natural bodies are propagated using a lookup method from pre-computed files. These ephemeris file names and locations are specified through the namelist inputs. In general, a reader can be set up to get position and velocity data from a file, conic approximation, or any other formula or data file for any participant.

- *Vector Rotation.* Rotational propagation is the generalized form of what is traditionally the method used to transform tracking station locations from body-fixed frames to inertial frames. The more general case allows not only for rotated stations, but also for a rotated spacecraft on any body, such as landers.

- *Integration.* Numerically integrated participants are traditionally spacecraft. The current integration propagator is a Runge-Kutta-Nystrom (R-K-N) seventh-order algorithm with eighth-order state control. This integrator can be used in fixed-step mode, where the integration step size is specified initially and remains constant, or in variable-step mode, where an error tolerance is used to determine the maximum step size that meets the specified error limit. Supported force models are listed in the appendix.

Output Data Displays

The displays connected to the ARTSN engine for output purposes are LabView graphical applications; any package with a TCP/IP network interface can be used to create an ARTSN real-time display. By using remote procedure calls across the network, a display can configure the engine to send the correct data stream back to itself without the user interacting directly with the engine. Front- and back-end displays can be implemented on relatively inexpensive desktop PCs while the engine runs on a workstation.

LabView provides a graphical dataflow language with which to create display applications[4]; Figure 5 shows the LabView-based Doppler observable display as it was used during the Mars Global Surveyor Mars orbit insertion.

Demonstrations

A validation of the ARTSN software was performed by comparison to the existing operations software (DPTRAJ/ODP). The agreement between the software suites was at the numerical precision level. Specific validation checks included:

- Trajectory and transition matrix integration

- Earth station location

- Observable and partial generation

- Batch filtering

- State and covariance mapping

After the initial checkout, there have been several opportunities to work with flight operations teams to demonstrate the capabilities of ARTSN. These collaborations have been valuable, as it significantly reduced the effort needed to gather all the relevant modeling inputs, and the navigation analysts on each mission have provided valuable feedback. Since no single particular mission captures all of the challenges presented to navigation analysts, it was important to interact with different projects whenever possible.

Mars Pathfinder

After the initial validation, ARTSN's first 'real world' tests was performed with Mars Pathfinder tracking data. The objective was to produce current state and epoch state solutions over a 76 day data arc. These solutions were then used to make encounter estimates; in both modes the ARTSN estimate agreed with that generated by the Pathfinder navigation team to within less than half of the Pathfinder estimate uncertainty, which is suitable for station predict generation and maneuver design. Figure 5 shows the comparison of B-plane[†] estimates for a set of ARTSN current state solutions to the solution prepared by the Mars Pathfinder navigation team.

A demonstration was also performed using an unedited recording of a DSN broadcast of the final two weeks of Mars Pathfinder before entry into the Martian atmosphere. This time span included the final trajectory correction maneuver, TCM-4, and a patch of data corrupted by the improper application of a leap second correction at the DSN. As the data was processed, the solution evolved, accounting for the maneuver and rejecting most of the corrupted data.

Mars Global Surveyor

The Mars Global Surveyor (MGS) navigation team demonstrated real-time navigation using ARTSN during the Mars Orbit Insertion (MOI) on September 11, 1997, and during the aerobraking phase of the mission to date. ARTSN read radio metric Doppler data in real time and computed measurements based on an ARTSN-generated nominal trajectory. Streams of observable and residual values were piped to several displays in real-time, both

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[†] The asymptotic approach plane at Mars.

to the public (see Figure 6) and the navigation analysts themselves.

The MGS navigation team continued to use the ARTSN displays and pre-processor to monitor aerobraking-related events, such as periapsis-lowering maneuvers, and tracking before and after each periapsis pass. The line-of-sight Doppler shifts during the maneuvers were reported back to the project as a 'quick-look' assessment of the event, and the effective Doppler shift from each aerobraking pass was also monitored as tracking resumed after each pass.

The ARTSN pre-processor (ARDVARC) is of special use to the MGS navigation team. The resumption of aero-braking in the Fall of 1998 will require the rapid turn around of navigation solutions as the mapping orbital period is reduced. ARDVARC's ability to correct and create tracking data files (for use with the current software) in real-time can significantly reduce the latency between the time the data is received and the time the analyst can begin working.

NEAR

In January 1998 the real-time display of ARDVARC was used to observe a small maneuver performed by the NEAR spacecraft. Output from the ARDVARC graphical display was used by the NEAR navigation team at JPL to notify the project that the maneuver had been executed. In order to more closely observe the maneuver, the Doppler count time was changed "on-the-fly" from 10 seconds to 1 second shortly before the maneuver. Once the 'quick look' assessment of the maneuver was complete, the count time was changed back to 10 seconds, in order to lower the volume of data to be post-processed. This ability to change the processing configuration in real-time has proven invaluable.

A month later, there was an opportunity to observe six thruster firings by the NEAR spacecraft. An annotated plot showing the results of this monitoring (see Figure 7) along with the Δ-V assessments, was prepared seconds after the end of the data arc shown._

Future Plans

With the successful series of demonstrations of high-fidelity orbit determination, ARTSN has served as a 'stepping stone' between the current paradigm of interplanetary navigation and a new paradigm with an emphasis on reliable automated processes. There are scenarios where an autonomous or nearly-autonomous presence would be of benefit, such as spacecraft trajectory predictions for ground tracking stations or autonomous orbit determination for a spacecraft in a long, quiet cruise phase.

The vision for ARTSN for the future will be realized through the development of the next generation navigation software system. The vision includes a significant expansion of its capabilities, especially in higher level optimization and regulating tasks.

References

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3. Moyer, T. D., "Mathematical Formulation of the Double Precision Orbit Determination Program (DPODP)," JPL Technical Report TR 32-1527, 15 May 1971.

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Appendix

ARTSN Computational Capabilities to Date

Participant Models
- Spacecraft and landers
- Tracking stations
- Natural bodies (planets, satellites, and small bodies)

Propagation Modules
- Runge-Kutta-Nystrom (R-K-N) seventh-order integration algorithm with eighth-order state control
- Body fixed rotation (for ground stations and landers)
- NAVIO planetary ephemeris
- NAVIO satellite ephemeris
- SPICE ephemeris

Spacecraft Geometry Model
- Flat plate, cylindrical and spherical component types
- Time-varying components
- Orientation in any coordinate system (including time-varying coordinate systems)

Force Models
- Newtonian and relativistic gravity and arbitrarily sized oblate gravity fields for any body
- Solar radiation pressure (using spacecraft component model)
- Finite and impulsive motor burns
- Arbitrary time-varying polynomial accelerations
- Atmospheric Drag (exponential density)

Body-fixed Ground Station Corrections
- Pole motion
- Plate motion
- Ocean, solid, and pole tides
- High precision time transformations

Coordinate systems (all are time varying)
- Cartesian, cylindrical, spherical, classical, B-plane types
- Body/Space, Mean/True, Equator, Orbital, Epoch/Of Date frames
- User defined coordinate frames (axes pointing at another participant, an inertial direction, or the velocity vector)
- Systems are defined and labeled, then referenced for use by all input and output routines
- Defined system can be configured to vary with time

Measurement Models
- Differenced range Doppler - 1, 2, and 3-way
- Range - 2 and 3-way
- Wet and dry Neill troposphere signal delays
- Participant delays
- Participant specific measurement biases
- Data editing (by checks for min. elevation angle, maximum allowable pre-fit residual)

Filter
- UD factorized, scaled Kalman filter
- Random walk, constant, and exponentially correlated random variable (1st order Gauss-Markov) process noise models
- Multiple batch mode (time bounded or number of measurement bounded batches)
- Current state Extended Kalman mode

Estimatable Parameters
- Spacecraft position and velocity
- Stations locations (Cartesian or cylindrical)
- Finite burn force, right ascension and declination
- Impulsive burns
- Solar pressure scale factor
- Solar pressure component scale factor
- Unmodeled accelerations
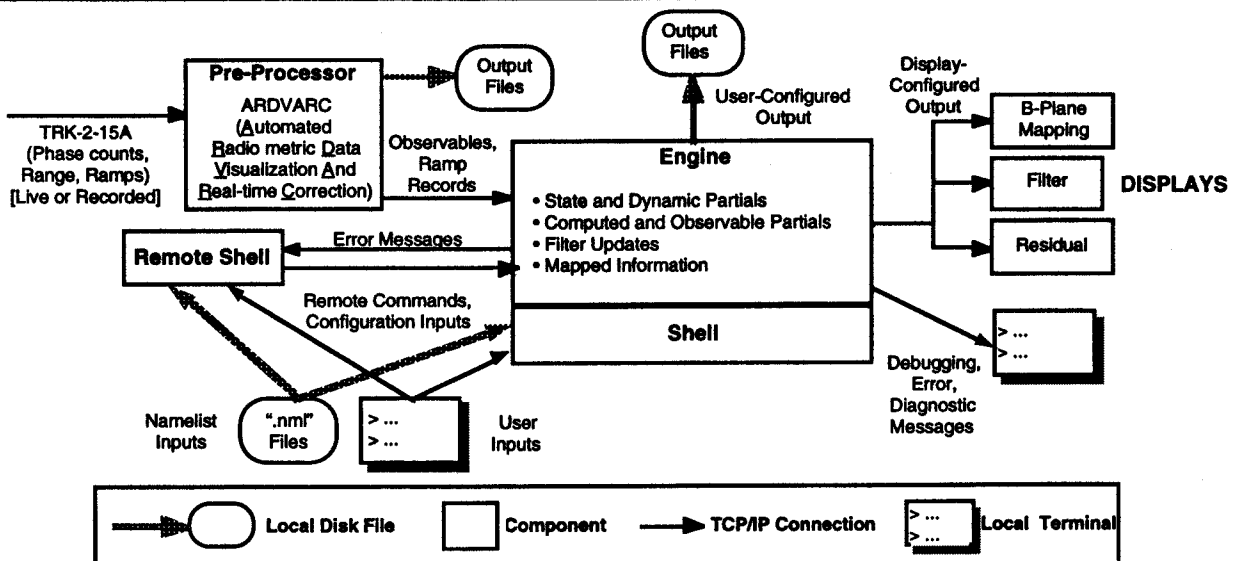- Measurement biases (for each participant)
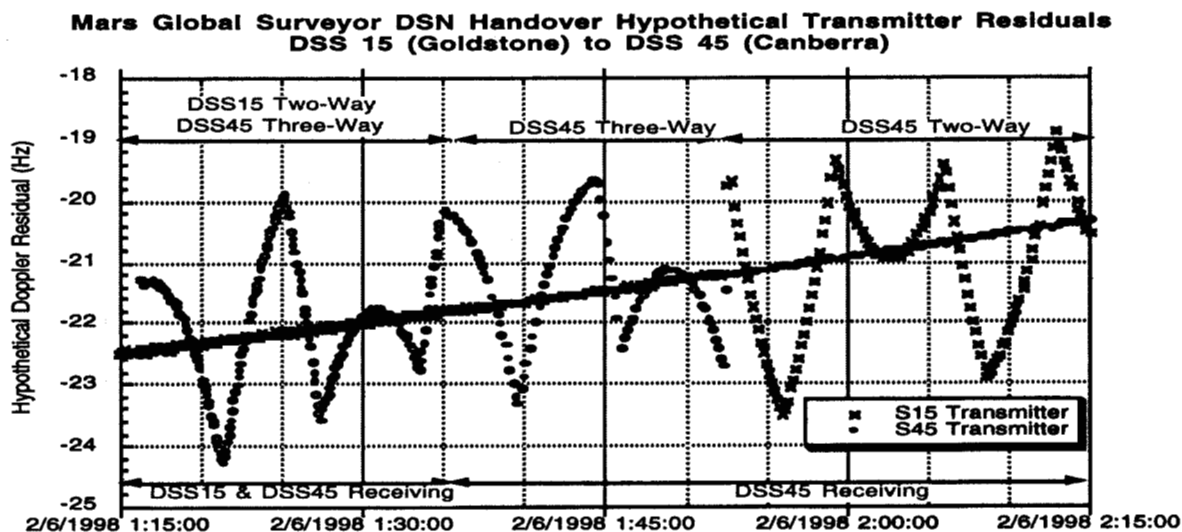

Figure 1. ARTSN Data Flow Diagram

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Mars Global Surveyor DSN Handover Hypothetical Transmitter Residuals
DSS 15 (Goldstone) to DSS 45 (Canberra)

Figure 2. Mars Global Surveyor Doppler Residuals Based on Two Different Transmitter Hypotheses
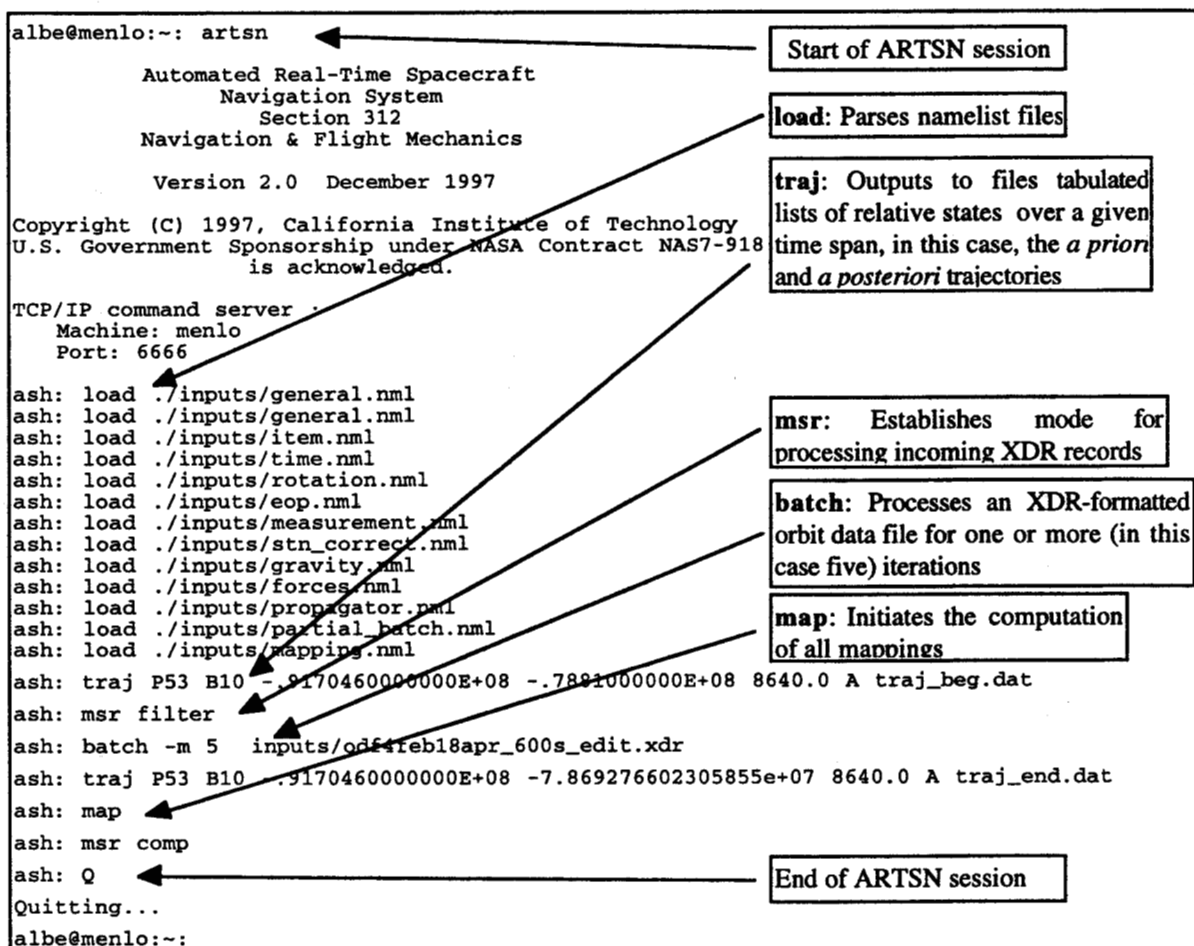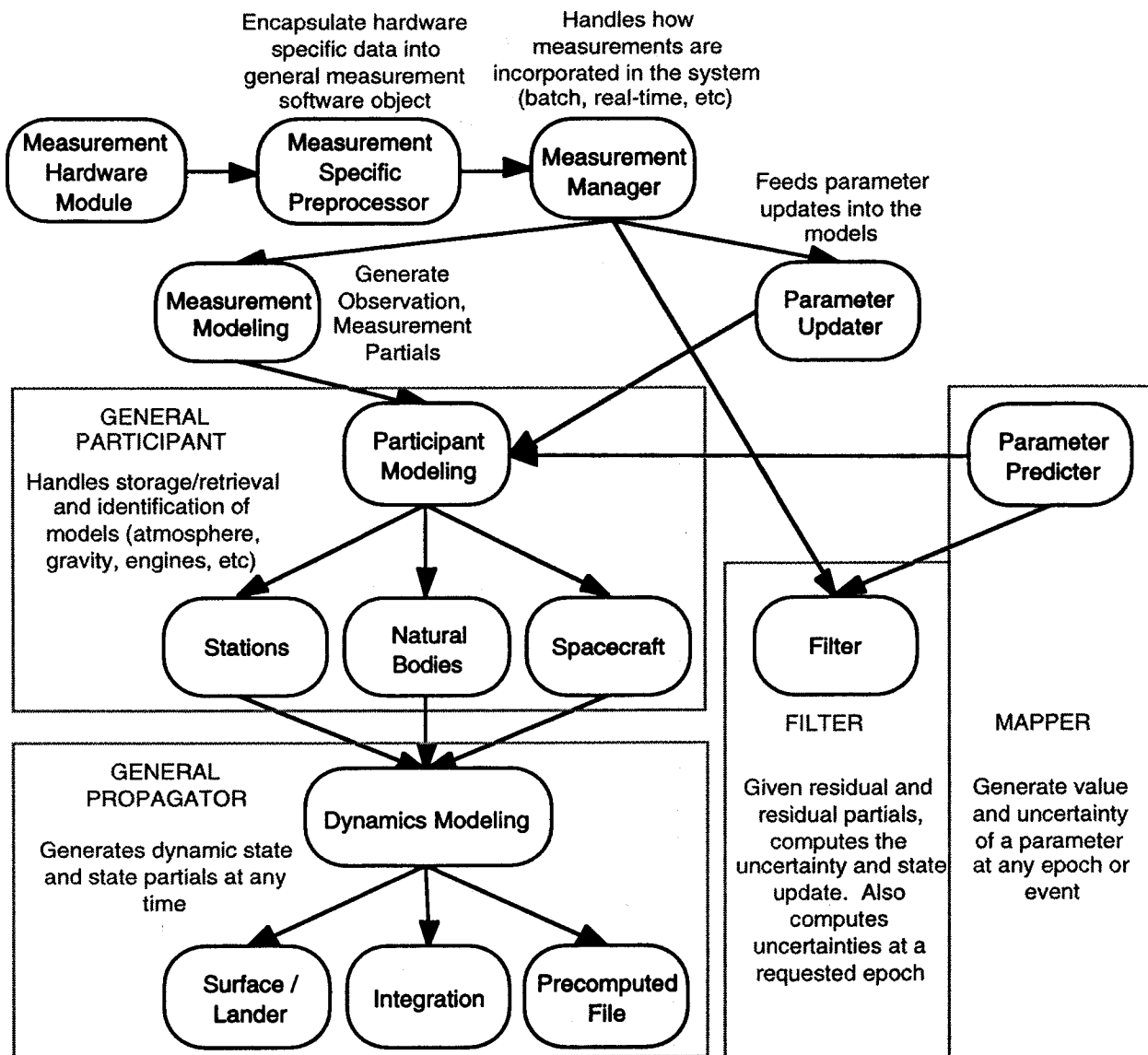

Figure 3. ARTSN Shell Session

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Figure 4. ARTSN Task Breakdown Diagram

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Orbit Determination Solutions: B-Plane Locations
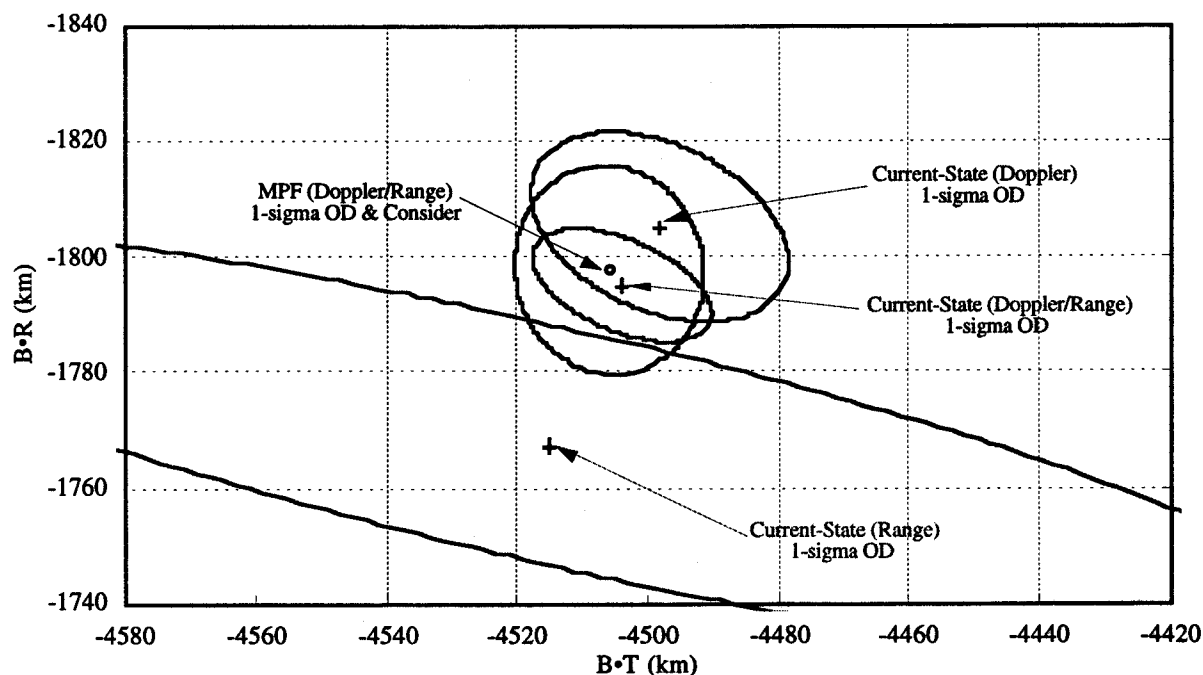## Mapping Frame: Mars-Centered Mars Mean Equator of 2000

Figure 5. Comparison of ARTSN Current-State Mapped B-Plane Estimates vs. Solution Prepared by Mars Pathfinder Navigation Team

Note: The Mars Pathfinder (MPF) B-Plane ellipse contains orbit determination (OD) uncertainty as well as consider parameters; the ARTSN ellipses contain only OD uncertainties.

	MPF Doppler/ Range	ARTSN Doppler/ Range	ARTSN Doppler Only	ARTSN Range Only
B•R	-1797.62	-1795.3	-1805.3	-1767.6
B•T	-4505.82	-4504.1	-4498.4	-4515.3

Planetary targeting is usually expressed in terms of the B-plane, a plane passing through the center of a target planet and perpendicular to the incoming approach hyperbola asymptote of a spacecraft. "B•T" is the intersection of the B-plane with the ecliptic and "B•R" is a 'southward' pointing vector in the B-plane that is perpendicular to B•T and making a right handed system R, S, T, where S is the incoming asymptote.

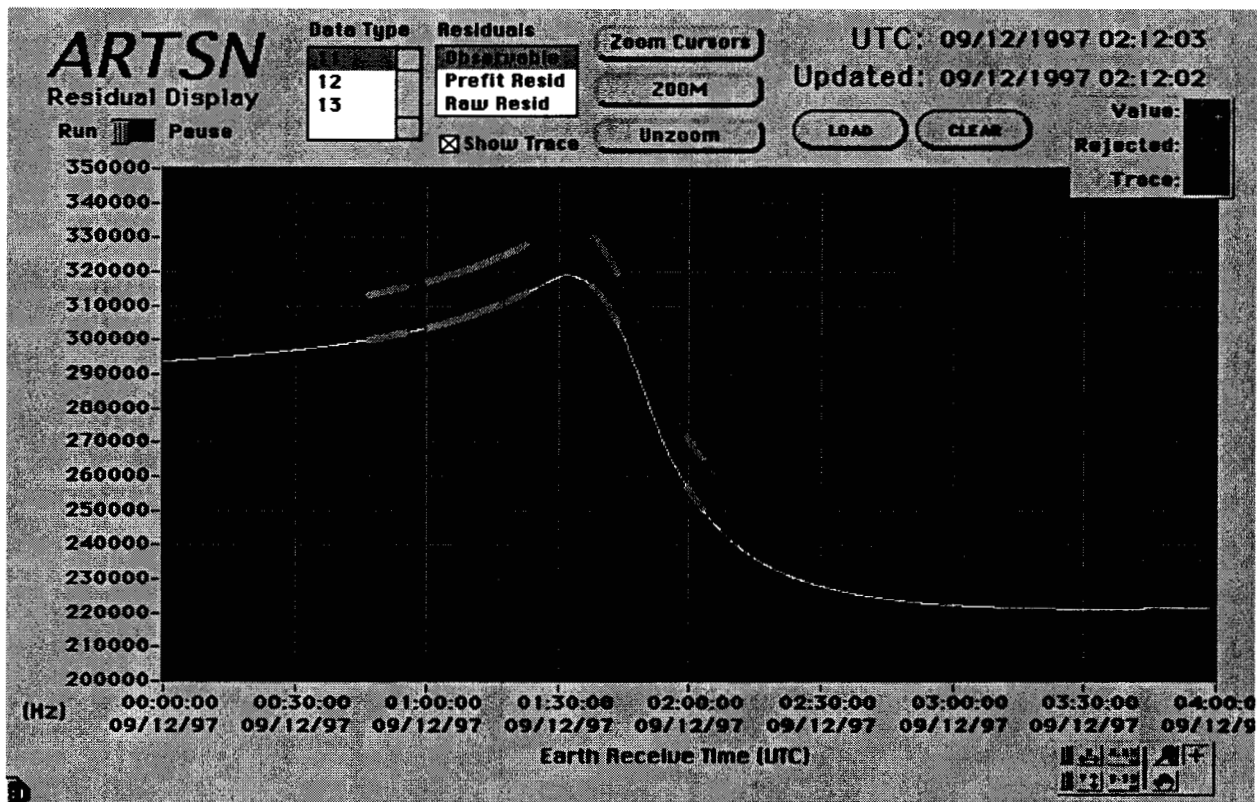American Institute of Aeronautics and Astronautics

Figure 6. ARTSN Display of Doppler Observables Shown on the JPL/MGS Home Page During MOI
Top Trace - Predicted 1-way Doppler Obs. for DSS 15 for a nominal MOI
Bottom Trace - Predictions for DSS 45, Heavy Traces - Processed Doppler Observables
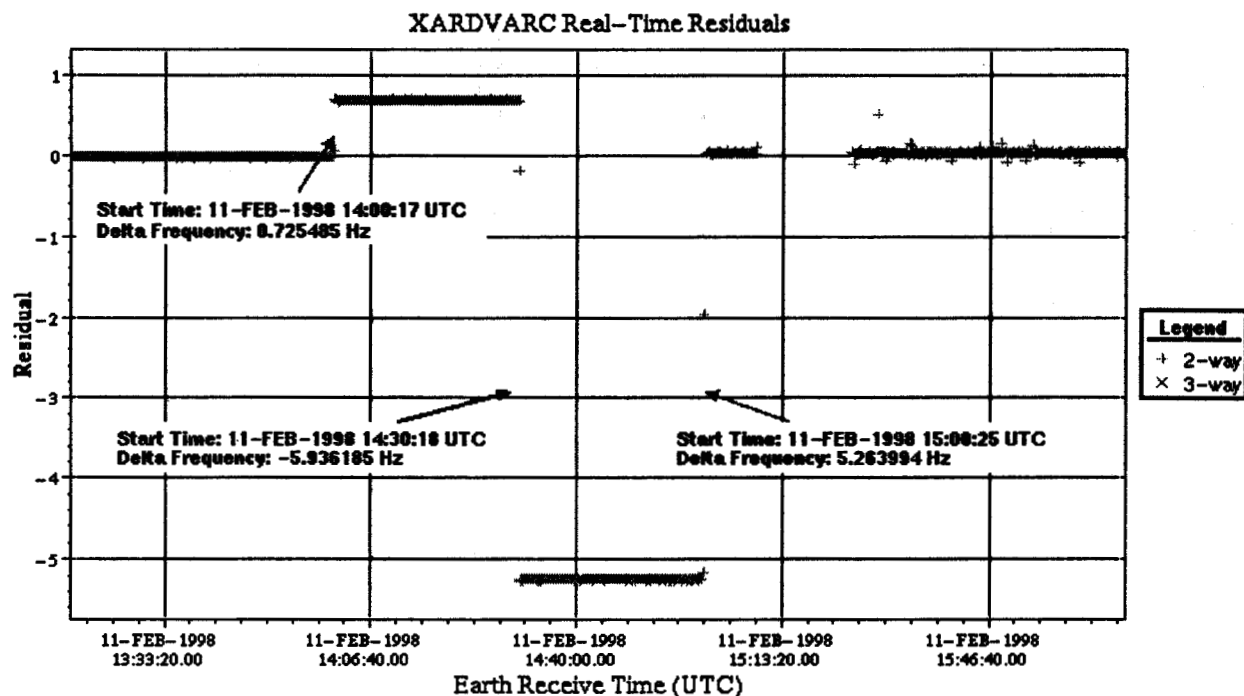

Figure 7. NEAR Doppler Residuals on 11-FEB-1998 (XARDVARC display, ARDVARC Delta-Freq. estimates)

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